A NEW METHODOLOGY FOR HEALTH HAZARD ASSESSMENT OF REPEATED SHOCK IN MILITARY TACTICAL GROUND VEHICLES

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ABSTRACT

This paper summarizes the outcome of an Army research program that culminated with adoption of a new standard of the International Standards Organization (ISO) and the development of a new methodology for health hazard assessment (HHA) of repeated shocks encountered in Army tactical ground vehicles (TGVs). This fills a gap in the existing ISO whole-body vibration standard, which does not adequately predict TGV occupants' lower back injuries that may be due to repeated shocks. Both Part 1 and the new Part 5 of ISO 2631 standard were implemented in an interactive graphical user interface (GUI) tool and transitioned to users who conduct HHAs of Army systems. As reported here, the GUI tool was used to compare the two standards. The comparison shows that the old standard often fails to detect adverse health effects of repeated shocks, which are clearly identified and accounted for by the new standard method.

1. INTRODUCTION

The health hazard assessment (HHA) is a program established by the U.S. Army with the overall objectives to increase war-fighting capabilities. Those objectives include preventing combat casualties and avoiding performance decrements caused by routine operation of combat systems and reducing health-related readiness deficiencies (U.S. Department of the Army, 1992). Since repeated shock was identified as one of the potential hazards likely to be encountered during tactical ground vehicle (TGV) operations, medical assessors and safety officers applied existing standards that were developed primarily for civilian applications and not necessarily for military scenarios.

In the mid 1980's, field reports attributed adverse health effects to whole-body vibration (WBV) exposure in military TGVs, even though these vehicles passed existing WBV standards. According to one such anecdotal report, "hematuria was observed in 50% of the company" after completing a military exercise mission. Although no systematic surveys were conducted among Army TGV riders, there were sufficient anecdotal reports from the field to raise concerns over the validity of existing WBV standards.

As a result of these concerns, the U.S. Army Aeromedical Research Laboratory (USAARL) was requested to investigate the applicability of existing WBV standards to TGVs operating in military scenarios and to develop a militarily relevant standard to use in evaluating occupant response to the repeated jolt environment that is commonly encountered in military tactical vehicles. The USAARL then embarked on a multi-year, multi-phase research program that culminated in the development of a new HHA method, the proposal and adoption of a new International Standards Organization (ISO) standard, and the development of a graphical user interface (GUI) tool that implements the complete methodology.

Application of the new HHA method extends well beyond the TGVs to other Army vehicles where the crew may encounter whole-body vibration and repeated shocks. The U.S. Army modern Stryker light armoured vehicle mobile guns system (LAV-105 MGS), shown in Figure 1, is one example where multiple shocks are likely to be encountered by its crew, either when it travels at high speeds over rough terrain or when it recoils during the firing of its 105-mm gun.

Figure 1. The Army Stryker LAV-105 MGS.

Much of the information presented here is drawn from a series of contractor reports written for USAARL by investigators from the British Columbia Research Institute (BCRI), the prime contractor who performed most of the research effort. (Village et al, 1995a; Roddan et al, 1995; Village et al, 1995b; Cameron et al, 1996; Morrison et al, 1998; Cameron et al, 1998).

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2. RESEARCH APPROACH

A five-phase research program was designed to develop a standard method for HHA of mechanical shock and repeated impact in Army TGVs. The experimental work was conducted at the USAARL multi-axis ride simulator (MARS) facilities in Fort Rucker, Alabama, and the data analysis and model development were completed at the BCRI facilities in Vancouver, British Columbia, Canada. A detailed account of the BCRI/USAARL research effort is given in a series of Contractor Reports by the BCRI team and summarized in a final report on Phases 1-5 (Cameron et al, 1998). The following is a brief description of the research and a summary of the findings.

2.1 Phase 1 – Literature Review

Most of published studies agree that long-term exposure to vibration accelerates onset of lumbar spine disorders, and possibly adversely affects the gastro-intestinal and cardiovascular systems. Few studies investigated human responses to repeated shock, but none investigated recovery. The review suggested potential approaches to development of an HHA method based on physiological, biochemical and biodynamic responses. Some biodynamic models, which range from single degree of freedom to three-dimensional and discrete parameter models, may have direct relevance to the development of a health hazard assessment method (Village et al, 1995a).

2.2 Phase 2 – Characterization of TGVs signatures

WBV signatures from seven military vehicles, tested at Aberdeen Proving Ground, Maryland, were processed and characterized. Over 580 tri-axial acceleration signatures were collected from the M1A1 tank, M1A1 HTT, M1026 HMMWV, B109A3 self-propelled howitzer, M923A2 5-ton cargo truck, XM1076, and the M2HS Bradley fighting vehicle. A procedure was developed to create generic motion signatures that simulate the shock and vibration environment of TGVs (Roddan et al, 1995). Using this procedure, a motion signature was created mathematically to realistically simulate the motion environment of TGVs by synthesizing two signals: one to characterize the shocks, and the other to characterize the near-continuous background vibration (Roddan et al., 1995). This allowed the use of a handful of generic signatures to represent the majority of those that may be experienced in vehicles operating in military scenarios. These generic signatures were then used to drive the motion platform of MARS at Fort Rucker, Alabama, during subsequent experiments in Phases 3 and 4.

2.3 Phase 3 – Pilot Study

Ten subjects participated in pilot tests using the MARS facilities in Fort Rucker to determine the most sensitive human response measures to mechanical shock and repeated impact for use in the development of the experimental phase and in a dose-effect model. Spinal acceleration, internal pressure, chest and abdominal displacement measurements and electromyographic (EMG) activities showed similar frequency response patterns to the shocks applied at the seat and to the seat accelerations (Village et al, 1995b). The similarity suggested seat acceleration might be used as the input parameter to the lumbar spine response models. The pilot study also recommended that such models should account for non linearity of response; differing horizontal and vertical inputs; and differing responses to positive and negative directions of shocks in the forward (x) and vertical (z) axes.

2.4 Phase 4 – Experimental Study

Fifty-four healthy, 19-40 year old U.S. Army soldiers volunteered to participate in a series of motion exposures at the MARS, which simulated realistic WBV and repeated jolt scenarios likely to be encountered during TGV rides. Some of the tests were short duration and were designed to assess relative severity of shocks. In the long-duration experiments, subject fatigue and recovery were evaluated by exposing them to TGV ride signatures for up to 7 hours/day, or 4 hours/day for 5 days. The study concluded that biomechanical responses at the spine depended on shock axis, amplitude and direction, with largest response resulting from vertical shocks. Subjective severity ratings to individual shocks were highly correlated with spinal acceleration. Subjects tolerated a 8-hour vibration dose value, or VDV(8), that exceeded the limit of 15, recommended both by the existing British Standard BS 6841 (British Standards Institute, 1987) and adopted in the ISO standard 2631-1 (International Standards Organization, 1997). Some subjects were able to tolerate a VDV(8) of 66 over a 7-hour period, or a VDV(8) of 60 over a 5-day period, without apparent health effects (Cameron et al, 1996).

2.5 Phase 5 – Recommendations for a HHA Method

In the final phase of the USAARL research program, BCRI recommended that the HHA method incorporate: (a) biodynamic models to predict spinal acceleration, (b) regression models to predict peak compressive stress at the L4/L5 lumbar joint, (c) given peak acceleration, a fatigue-based model to quantify the cumulative effects of repeated shocks, and (d) an injury probability model that relates the cumulative dose to the probability of spinal injury within a normally distributed population (Morrison et al, 1998).

3. HHA METHOD FOR REPEATED SHOCKS

Based on its recommendations at the conclusion of Phase 5 (Morrison et al, 1998), BCRI developed a new HHA methodology that incorporated four distinct models, as described below.

3.1 Biodynamic Lumbar Spine Response Models

Response to horizontal seat accelerations (x and y axes) was nearly linear, suggesting that an existing linear model may be adequate. The dynamic response index (DRI) model, commonly used in evaluating ejection seats (Air Standardization Coordinating Committee, 1989) was used. The parameters were adjusted (Figure 2) and successfully used to predict the spinal response to horizontal seat accelerations with reasonably good agreement with measured response.

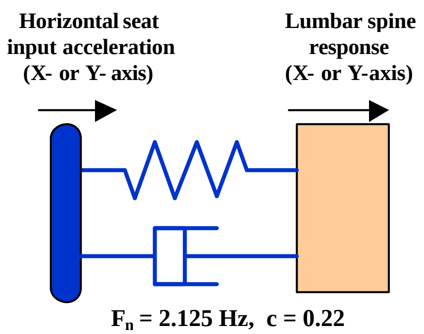

Figure 2. Single degree-of-freedom model for prediction of lumbar spine kinematics response in the horizontal axes.

For vertical axis (Z) lumbar spine response, a non-linear recurrent neural network (RNN) model (Figure 3) was developed and trained using measured accelerations.

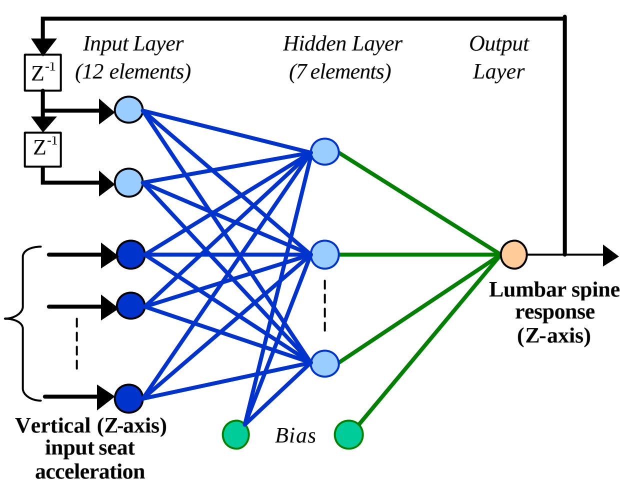

Figure 3. Recurrent neural network model to predict lumbar spine response to multiple shocks in the vertical direction.

3.2 Biomechanical Spinal Response Model

A biomechanical model was needed to calculate the compressive force at the L4/L5 lumbar joint given the predicted kinematics (accelerations) at that point. Such a model was developed and applied to the experimental data obtained from Phase 4 to provide information on the compressive forces generated at the lumbar L4/L5 joint in response to mechanical shocks in the x, y and z axes. This information then was used to relate the peak spinal accelerations predicted by the biodynamic response models to the compressive force acting on the L4/L5 lumbar vertebral joint. Details of this modelling strategy and the final biomechanical model may be found in the Phase 5 final contractor report (Morrison et al, 1998).

3.3 Cumulative Dose-Response Model

Given published data on vertebral compressive strength, the relationship between acceleration and forces at the L4/L5 disk was used to estimate the number of low-level shocks that would result in fatigue failure of the L4/L5 joint. By estimating spinal motion from seat acceleration (using dynamic models) and subsequently converting the estimated motion to force (using the biomechanical model), it was possible to develop a dose-response model to predict fatigue failure (i.e., injury) of the L4/L5 caused by repeated shocks.

3.4 The New ISO 2361-5:2004 Standard

The biomedically-based BCRI approach for modelling and assessment of repeated shock formed the basis for proposing an amendment to the existing ISO 2631-1 (International Standards Organization,, 1997). Since a similar USAARL-led effort was underway in the U.S. to develop a standalone American National Standards Institute (ANSI) standard that incorporates the BCRI method, the proposed ISO amendment and the draft ANSI standalone standard were combined and a new draft international standard (DIS) emerged which addresses specifically the repeated (or multiple) shocks. The new standard, which was adopted in 2003 and published in 2004, contains most of the elements of the modelling strategies that were developed by BCRI.

The new ISO 2631-5 standard (International Standards Organization, 2004) relies on the biodynamic models described above to generate acceleration response at the lumbar spine. Once the spinal accelerations have been generated, an acceleration dose ($\boldsymbol{D_x}$, $\boldsymbol{D_y}$, $\boldsymbol{D_z}$) is calculated by summing peak acceleration responses that exceed certain thresholds for each axis. The dose then is prorated based on duration of the available record and the expected length of the workday, to obtain $\boldsymbol{D_{xd}}$, $\boldsymbol{D_{yd}}$, $\boldsymbol{D_{zd}}$ and calculate the total daily exposure. Refer to the ISO document for full details of the calculations.

The new ISO standard provides, albeit in an informative annex, guidance for assessment of health affects of multiple shocks. The calculated total daily acceleration dose in the biocentric axes are combined to obtain an equivalent static stress compressive stress, $\boldsymbol{S_{ed}}$, as follows:

$$S_{ed} = [\,(m_x\, D_{xd})^{6} + (m_y\, D_{yd})^{6} + (m_z\, D_{zd})^{6}\,]^{1/6}$$

where $\boldsymbol{m_x}$, $\boldsymbol{m_y}$, $\boldsymbol{m_z}$ are constants for the three directions. A daily equivalent static compression dose, $\boldsymbol{S_{ed}}$, is then computed, and used to compute a risk factor, $\boldsymbol{R}$, for use in the assessment of the adverse health effects. For a typical career, the standard suggests that, $\boldsymbol{R} < 0.8$ indicates a low probability of an adverse health effect and $\boldsymbol{R} > 1.2$ indicates a high probability of an adverse health effect. This is equivalent to stating that $\boldsymbol{S_{ed}} = 0.5$ and $\boldsymbol{S_{ed}} = 0.8$ are the lower and upper boundary of a caution zone for a normal person during a typical working day. Again, the reader is referred to the ISO 2631-5 document for details of the calculations.

4. IMPLEMENTATION

4.1 The WBV-Jolt GUI Software

Although the new ISO 2631-5 provides a Matlab® code that implements the new method, a user-friendly interface was needed to facilitate the application of the HHA methodology to signatures collected at various seat locations during testing of new U.S. Army TGVs. Some of the features and requirements that were incorporated in the WBV-Jolt GUI tool included:

- Runs in a stand-alone mode (i.e., independent of any computation engine) on any desktop PC operating under Windows 2000.
- Implements ISO 2631-1 (WBV) and 2631-5 (Jolt) standards in the same software, because both use the same ride pad accelerations as a basis for evaluation.
- Displays time history plots of input signals, weighted acceleration and spinal response for visual inspection.
- Allows the reading of standardized-format text files, with no size restrictions, and accepts acceleration signatures samples at any sampling rate.
- Computes key parameters for WBV (e.g., ***rms***, ***VDV***) for multiple shock (e.g., $\boldsymbol{S_{ed}}$, $\boldsymbol{R}$) and appends new results to previous ones in an Excel file.
- Assigns "severity categories" based on separate WBV and jolt key parameters.
- Guides the user in assigning "probability levels" as defined in the Army HHA regulation (AR 40-10).
- Produces risk assessment codes (RACs) as required by the same HHA regulation.

4.2 Implementation of ISO 2631–1 and –5

The two ISO 2631 standards (Part 1 and Part 5) were implemented in a software program, Jolt 4.5, which incorporates all the desired features listed in the previous section (Alem et al, 2004a]. The software has been transitioned to the U.S. Army HHA program, where it has been successfully used to evaluate new Army systems. Figure 4 shows the flow of the data, processing, analysis and extraction of pertinent parameters that are used to define the severity category of the WBV and/or repeated jolt signature.

The Implementation starts with selection of the data folder that contains vehicle information such as ride pad signatures from ride quality testing of the vehicle in question. The file format has been standardized to allow ease of data exchange between test facilities and assessors. The software allows the user to verify the selected signatures by displaying the file header information. Once a file is selected, the signals are processed to remove any DC bias, apply an anti-alias filter, and resample at the rate of 160 samples per second. This sampling rate is a requirement by the ISO 2631-5 standard since the RNN model coefficients were defined specifically for input sampled at 160 Hz.

The resampled signal is frequency-weighted per ISO 2631-1 requirements, and put through the appropriate

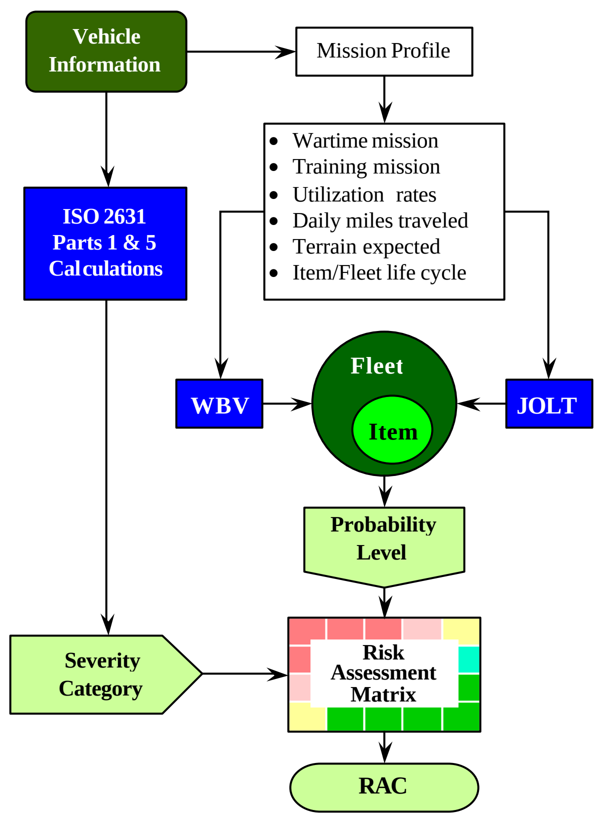

Figure 5. Block diagram of the complete HHA methodology.

biodynamic model per ISO 2631-5 procedures. Key parameters are extracted and saved for subsequent assessment steps. WBV parameters that are extracted include: the weighted root-mean squares (***Wrms***), peak acceleration and crest factor, ***VDV(8)***, and maximum transient vibration value (***MTVV***). The ***Wrms*** then is used to determine the lower and upper boundaries of the caution zone, defined in ISO 2631-1, Annex B.

For repeated shocks assessment, the spinal response signal is used to identify and count the number of peaks exceeding a certain threshold and to calculate the acceleration dose for the measurement duration, then prorate it for the expected daily exposure duration.

The normative portion of the new ISO 2631-5 standard ends with the calculation of the average daily acceleration dose, described above. The standard provides guidance for the assessment of health effects of multiple shocks in Annex A, an informative part of the standard. In order to provide a useful tool for the HHA community, the ISO 2631-5 guidance was implemented. The outcome is a risk factor ***R*** that is a function of several factors, including exposure days per year, age at start of exposure, years of exposure, as well as the estimated average daily stress derived from the average acceleration exposure dose.

To accommodate AR 40-10, USAARL defined four ranges of the daily exposure limit (i.e., upper boundary of the caution zone) and of the risk factor R that corresponds to the four severity categories defined in the AR. Those are given in Table 1, along with the corresponding ranges for the ***VDV(8)*** and the S_{ed}. The ***VDV(8)*** and S_{ed} are given for information purposes only and are not used in further steps of the HHA.

Table 1. Convention used by USAARL to assign severity categories of WBV and repeated shock.

Whole-Body Vibration ISO 2631-1		Repeated Shocks ISO 2531-5		HHA AR 40-10
WBV Daily Exposure Limit	Vibration Dose Value VDV(8)	Equivalent daily stress, ***Sed***	Risk factor, ***R***	Severity Category
< 10 min	> 21	> 0.95	> 1.4	I Catastrophic
10 – 30 min	13 – 21	0.65 – 0.95	1.4 – 1.0	II Critical
30 – 180 min	4 – 13	0.35 – 0.65	1.0 – 0.6	III Marginal
> 3 hours	< 4	< 0.35	< 0.6	IV Negligible

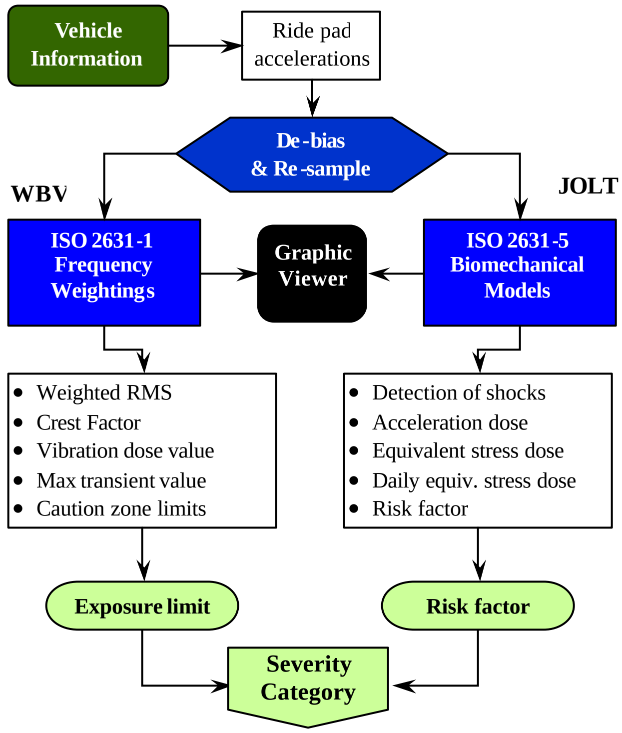

Figure 4. Block diagram of the simultaneous implementation of ISO 2631 standards (Part 1 and 5).

4.3 Extensions to Meet HHA Requirements

In order to complete the HHA process and produce a risk assessment code, as shown in Figure 5, it is necessary to assign a probability level for the WBV and repeated shock exposure. HHA experts agree that these levels must be based on the mission profile of the item (or its fleet) and the frequency of its usage. There are no set guidelines for this process, so that one must judiciously evaluate the mission and assign a probability of exposure, perhaps in consultation with the vehicle user. The assigned probability levels must conform to the classifications given in AR 40-10, shown in Table 2.

Table 2. WBV and repeated shock hazard probability, as defined in AR 40-10.

Probability		Likelihood of occurrence	
Level	Label	in a *vehicle*	in the *fleet*
A	Frequent	Frequently	Continuously
B	Probable	Several times	Frequently
C	Occasional	Sometime	Several times
D	Remote	Unlikely, possible	Unlikely, expected
E	Improbable	May never occur	Unlikely, possible

5. EVALUATION

The USAARL conducted a study to compare the three assessment methods prescribed in the existing ISO 2631-1:1997 and the new ISO 2631-5:2004. All three methods use the same ride pad signature as input to the data analysis but often produce different assessments, as will be demonstrated in this section.

5.1 Data Processing

Ride pad accelerations were obtained from a dozen military vehicles, including tactical ground and water vehicles, tracked and wheeled. All signatures were from seat cushion pads. Run conditions varied with terrain type, vehicle speed, and seat location. All vehicles were driven and occupied by healthy adult males who were seated upright.

WBV-Jolt software (version 4.5) was run in batch mode on all available signals and summaries were saved on Microsoft Excel files. The summaries included, for each triaxial ride pad signature, the vehicle and seating information, terrain type and speed to help explain any unusual outcome.

5.2 Evaluation Methods

Three evaluation methods were compared:

- *The RMS method:* the total root-mean square of the weighted acceleration a_w, (also referred to here as ***Wrms***) which is described in ISO 2631-1:1997 as the basic evaluation method.
- *The VDV method*: the vibration dose value normalized to an 8-hour day, ***VDV(8),*** also described in ISO 2631-1:1997 as an additional method to use when the basic method is not sufficient to account for shocks that are embedded in the WBV signal.
- *The Jolt method*: the equivalent static compression dose, S_{ed}, which is derived from acceleration shocks dose and normalized to average daily exposure time, as described in the new ISO 2631-5:2004 standard.

In normal applications, the S_{ed} is used to calculate the risk factor ***R*** (discussed earlier), which takes into account the number of years and days per year of exposure and factors in the vertebral bone ultimate strength, which in turn depends on the age of the vehicle occupant at the time of exposure. Since the other two methods, ***Wrms*** and ***VDV(8)***, do not incorporate lifetime exposure, the basis of comparisons in this paper was restricted to the S_{ed} parameter.

5.3 Results and Discussion

A total of 1044 triaxial signatures were processed and analyzed. However, a much smaller sample of signatures is included here for discussion.

Over 90 percent of available signals were excluded from this discussion since the three evaluation methods indicated *negligible severity category* (SC) for these signals. There were approximately 70 runs whose ***Wrms***-based SC was different from the S_{ed}-based SC, indicating the presence of significant levels of shock. Nearly half of those runs had comparable SCs to the other half and were, therefore, not selected for further discussion. The remaining 40 runs were deemed appropriate and relevant for this paper. Visual inspection of these signals confirmed the presence of multiple shocks, as indicated by SC = 1 or 2 (see Table 1 for SC definitions). The detailed results of this procedure are reported elsewhere (Alem et al., 2004b).

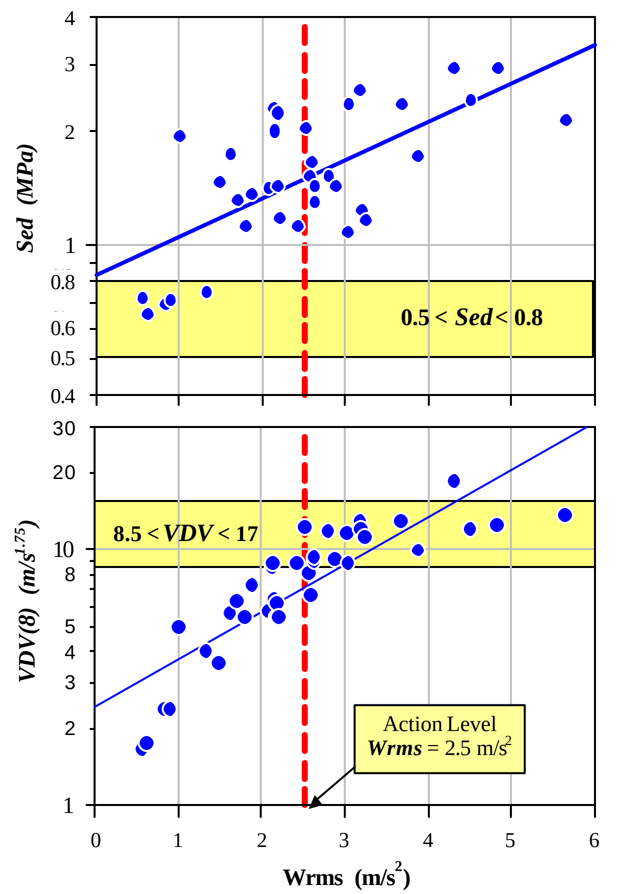

Figure 6. Plots of the S_{ed} and ***VDV(8)*** against the ***Wrms***, showing the recommended caution zones (horizontal bands) and action level (vertical dashed line.)

A graphical comparison of the three methods is given in the two plots of Figure 6. The horizontal bands represent the caution zones that are essentially recommended in ISO 2631-5 and in both ISO 2631-1 as well as the action level of ***Wrms*** = 2.5 m/s^2 set by EU Directive 2002/44/EC (European Parliament, 2002).

Although both the $\boldsymbol{S_{ed}}$ and the ***VDV(8)*** appear to correlate to some extent with the ***Wrms***, which is the basic parameter for WBV assessment, the ***VDV(8)*** of half of the signatures fell below the lower boundary of a caution zone that is essentially defined in ISO 2631-1 and the EU directive. In other words, the ***VDV*** method would have failed to alert the assessor of potential hazard of repeated shock in 50% of the cases that are known to contain significant shock levels. On the other hand, most of $\boldsymbol{S_{ed}}$ values of the same signatures exceeded the upper boundary of the corresponding caution zone, an appropriate indication that a potential repeated shock hazard exists is associated with these signatures.

One explanation for the failure of the ***VDV*** to detect signatures with high shock contents is that the threshold currently recommended in the ISO 2631-1 may be too high. Figure 7 shows that there is a reasonable linear correlation ($R^2 = 0.45$) between the ***VDV(8)*** and the $\boldsymbol{S_{ed}}$:

$$\boldsymbol{VDV(8)} = 4.11 \times \boldsymbol{S_{ed}} + 1.47$$

In order for the ***VDV(8)*** to be used for detecting high shock content in a vibration signature, the threshold should be lowered. If one accepts the correlation shown here, then the lower and upper boundaries of a ***VDV(8)*** "caution zone" would be 3.5 and 4.8, respectively. With these "caution zone" thresholds, the majority of the cases would be detected as requiring further analysis, but some would still go undetected.

6. SUMMARY & CONCLUSIONS

A new methodology to evaluate whole-body vibration containing multiple shocks has been developed. Unlike existing repeated shocks evaluation methods (e.g., the vibration dose value) that are based on mathematical properties of a WBV signal, the new method is based on biomechanical response of the lumbar spine. Application of the new method is limited to seated healthy adult males. The methodology includes a new ISO 2631-5 standard; the WBV-Jolt software, and the HHA extensions that implement AR 40-10.

The ability of the new method to discriminate the presence of shocks in the WBV signature was compared to those of other methods and was shown to correctly detect the presence of high levels of shocks in a WBV signature. This is not to say that the new method was able to predict injury from these signatures since these were test signatures and did not have injuries associated with them. Prospective monitoring of the occupational health of vehicle operators over their careers will be required to eventually validate the accurate injury-prediction capability of the new method. Although low- and high-risk thresholds were defined for the new method, these limits were based on the best biomechanical data

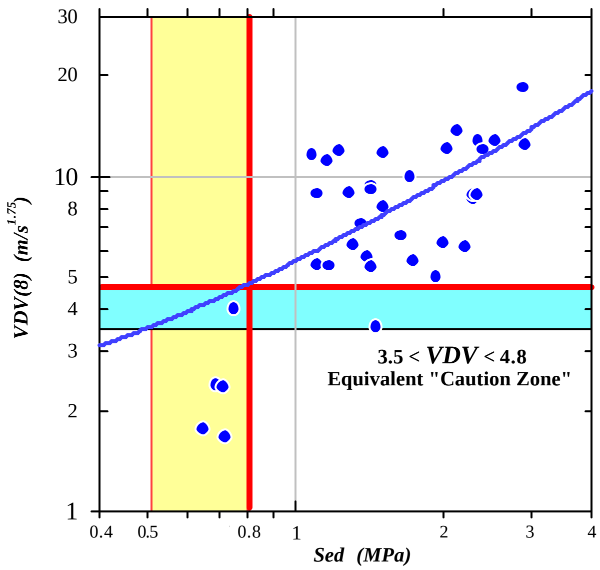

Figure 7. Cross-plot of ***VDV(8)*** against $\boldsymbol{S_{ed}}$, showing the ***VDV(8)*** of 84% of repeated shocks signatures exceed a level of 4.8 $m/s^{1.75}$ ($\boldsymbol{S_{ed}}$ = 0.8 MPa).

available on lumbar spine vertebrae strength and failure. These threshold values should be monitored and, if necessary, revised based on credible new data that might be generated in the future.

7. RECOMMENDATIONS

- When screening WBV signatures for high shocks, use as many valid methods as possible.
- Use the ***VDV*** method as a screening tool but reduce the trigger threshold to ***VDV(8)*** = 3.5 $m/s^{1.75}$. Do not use the ***VDV*** method for assessment of repeated shocks.
- Conduct prospective surveys to monitor the lumbar spine health of military vehicle drivers.
- Review credible new data to confirm/amend the action values defined in the new method.
- Conduct further research to extend the new method to other seated or recumbent postures.

DISCLAIMER

The opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the U.S. Army and/or the Department of Defense.

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